defra
Department for Environment
Food and Rural Affairs

Met Office
Hadley
Centre

Climate change, rivers and rainfall

Recent research on climate change science from the Hadley Centre

December 2005

Summary

- The global average temperature for 2004 was around 0.75 °C above that at the end of the 19th century, making it the fourth warmest year on record.
- There is now strong evidence that extremes of rainfall over land have changed during recent decades. However, some areas do experience changes opposite to the global average trends.
- There is evidence that human activity is changing river flows, both directly through global warming and through the effect of increasing carbon dioxide on plant behaviour.
- Predictions from Hadley Centre climate models show that further increases in temperature and rainfall are expected during the 21st century. Temperature is expected to increase almost everywhere but with rainfall the pattern of change is more variable — it will increase in some areas but decrease in others.
- Comparison of the Hadley Centre predictions of future rainfall with those from other climate models from around the world highlights the large uncertainty in predictions. The Hadley Centre is trying to measure this uncertainty and to reduce it.
- Increases in river flow are also predicted for the 21st century but, as with rainfall, some areas are expected to see an increase and others a decrease.
- The African continent has already experienced the severe impacts of drought conditions. We predict that, in the future, further reductions in rainfall over parts of Africa are likely.

Introduction

Current research

In this Hadley Centre report we describe some of the most recent climate change research. This year, our focus is on the water cycle, which plays a key role in the impact of climate change on the human and natural environment. It is well known that in a warmer world the water cycle is likely to intensify. This could alter the patterns of precipitation and river flow with potentially large consequences for society through, for example, changes to water availability, food production and flood risk. Ecosystems may also be affected.

In **part one** of the report we present observations showing how and where the water cycle is changing and the current evidence of a human fingerprint in the observed pattern of change. In **part two** we use predictive models to examine how climate and the water cycle might change over the coming century, looking at both precipitation and river flows. Finally, in **part three** we discuss a case study of how the African climate has altered and how it might change further in the future. We chose this region because, along with climate change, it was a focus of the G8 nations during the period of the United Kingdom's presidency.

The Hadley Centre

The Met Office's Hadley Centre for Climate Prediction and Research was established in 1990 and now employs 150 scientists and support staff. The Met Office's supercomputer is amongst the most powerful in the United Kingdom and is capable of two million million calculations per second. The aims of the Hadley Centre's climate research continue to be to:

- monitor climate variability and change on global and national scales;
- attribute recent changes in climate to specific natural and man-made factors;
- understand the processes within the climate system and develop comprehensive climate models which represent them;
- use climate models to simulate global and regional climate change over the last 100 years, and to predict changes over the next 100 years and beyond;
- predict the impacts caused by climate change, such as the availability of water resources and capacity for food production.

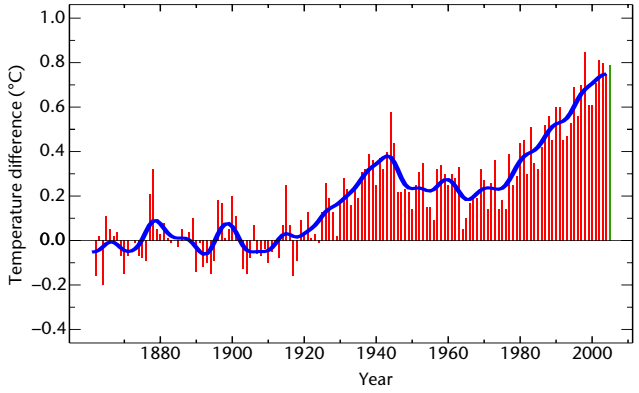
Some regions of the world will become more prone to flooding, while others will experience water shortages

Observed changes in temperature and precipitation

Recent climate change

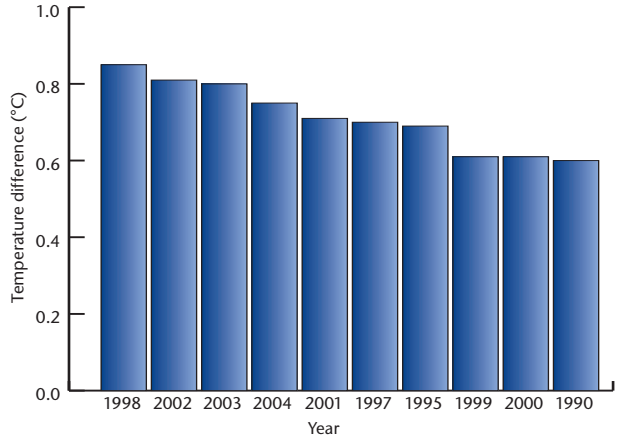
The global average surface temperature rise from the mid 19th century to the present day is shown in the Figure below. The temperature for 2004 was around 0.75 °C above that at the end of the 19th century, making it the fourth warmest year on record. The temperature rise for 2005, including the observations from January to August, is shown in green. Predictions suggest this may become the second warmest year on record by December.

Observed global average surface air temperature change, measured relative to the end of the 19th century (combined land and sea results)



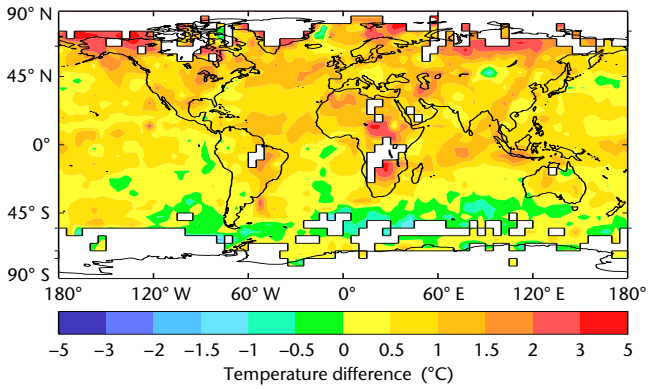
The two periods of most rapid warming were during the 1930s and since around 1970. The top 10 annual average temperatures in the instrument record (since 1860) are listed in order in the Figure below. It is notable that they have all occurred since 1990.

The top 10 warmest annual average global temperatures since 1860. The temperatures are given as an anomaly relative to the end of the 19th century



Temperature anomalies for 2005 up to August (Figure below) show large areas of the Northern hemisphere and Africa exhibiting temperatures of between 2 and 5 °C above the average for the same period at the end of the 19th century.

Temperature anomalies for Jan–Aug 2005, relative to the end of the 19th century

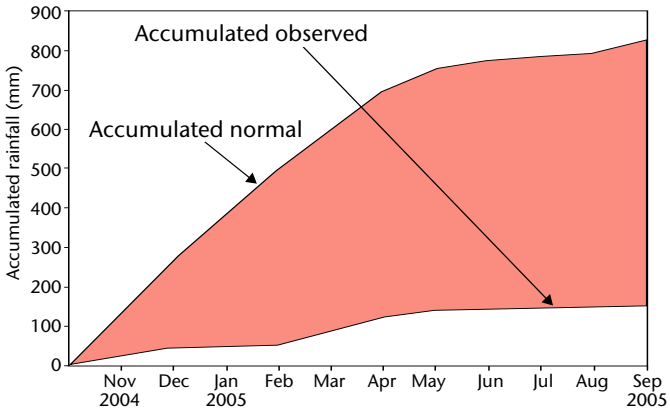


Drought in the Iberian Peninsula

This year, Spain and Portugal have suffered from water shortages. The hot dry summer in 2005 followed a period of drought in the winter of 2004–2005. In Portugal, 97% of the land area was afflicted with severe to extreme drought. These were the most severe conditions since the 1940s, and a contributing factor to the forest fires which have caused widespread destruction in this region.

The Figure below shows a massive deficit in the accumulated rainfall over the Portugese capital, Lisbon, for the period November 2004 to September 2005. Rainfall totals over the period exhibit a highly unusual deficit of 77%. Using a climate model simulation this was estimated to be a less than 1-in-400-year occurrence. Large deficits for the same period are apparent in other major Iberian cities, including Madrid.

Accumulated rainfall over Lisbon



Observed changes in average and extreme precipitation

Most analyses of long-term global climate observations of surface temperature and precipitation have focused on the change in annual or seasonal average values. However, extremes often cause the biggest impacts, both in terms of flooding and of drought. Recently, daily data from a large number of regions from the period 1951 to 2003 have been used to look for evidence of observed climate change in temperature and precipitation extremes. In total, observations from around 6,000 sites were included. Trends were calculated only for the locations with at least 40 years of data with an end date after 1998.

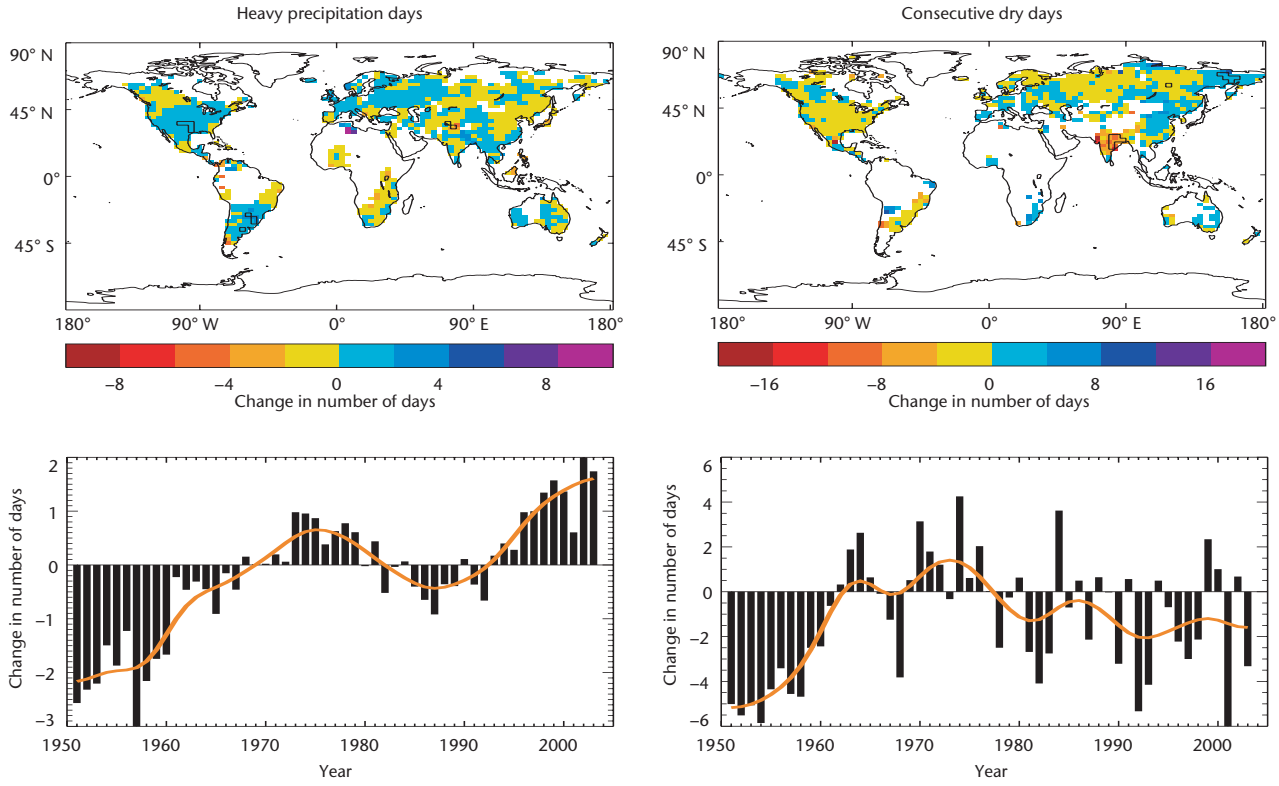
The adjacent table and Figures below show that there is strong evidence that extremes of rainfall have changed during recent decades. However, significant trends are much less widespread for precipitation than they are for temperature.

Table of changes in extremes of precipitation between 1951 and 2003

No. of days with:	% of land area sampled with a significant increase	% of land area sampled with a significant decrease	Significant changes in global mean
Precip> 10 mm	8	7	increase
Precip> 20 mm	12	5	increase
Very wet days number	11	3	increase
Consecutive dry days	4	7	–

In addition, over 15% of the land area sampled had significant increases in the intensity of precipitation and only 3% had significant decreases.

The change in the number of days with heavy precipitation (left) and the number of consecutive dry days (right). The upper diagrams show the spatial distribution of significant trends while the lower diagrams show the spatial average anomolies (relative to 1961–1990) for each year



Observed changes in river flow – why is it changing?

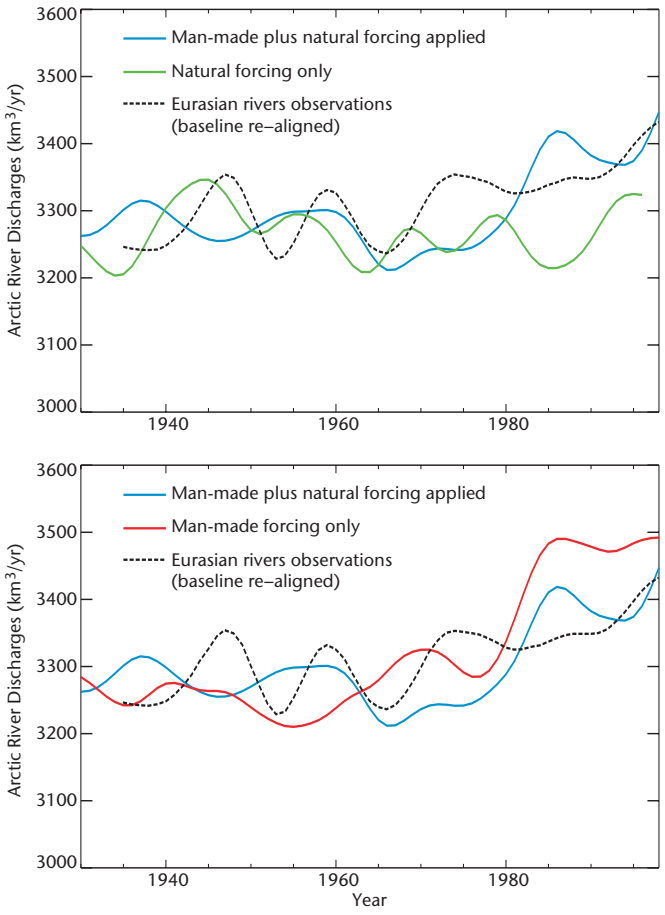
Arctic river flow

Water flowing out of rivers into the sea 'freshens' the seawater, making it less salty. Changes in the freshening of the Arctic ocean due to this and other causes could have major implications for global climate by altering the large-scale ocean currents that transport heat from the tropics to high latitudes. Previous results have shown that increased freshening and a resulting disruption in the ocean heat transport could cool much of the northern hemisphere, with large socio-economic and environmental impacts.

A major source of freshwater into the Arctic ocean is river flow from the Eurasian rivers. Recent observations[1] show there has been an increase in the total amount of water flowing from the six largest Eurasian rivers into the Arctic during the 20th century. The Hadley Centre has used one of its climate models to simulate the river flow into the Arctic during the 20th century, with both man-made and natural climate change included. A simulation of what the 20th century changes in Arctic river flow might have been like if there had been no interference from man (so called natural forcing only) was also produced.

When only natural forcing was included, the model simulation did not have a clear trend. However, when natural and man-made effects were included, the model showed an increase in the Arctic river flow from the 1960s, consistent with the observations. This suggests that the man-made climate forcing is a major cause of the increased river flow.

Comparison of observed and modelled discharge into the Arctic, taking into account natural and man-made factors separately in the simulations



Present day freshwater discharge into the Arctic from Eurasian river catchments

River	Average observed flow 1936–1999 (km³/yr)	Average observed flow 1990s (km³/yr)
Yenisey	620	653
Lena	530	537
Ob	404	407
Kolyma	132	136
Pechora	141	149
S. Dvina	105	117

[1] Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vorosmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiklomanov, and S. Rahmstorf (2002), Increasing river discharge to the Arctic Ocean, Science, 298, 2171- 2173.

Continental changes in river flow

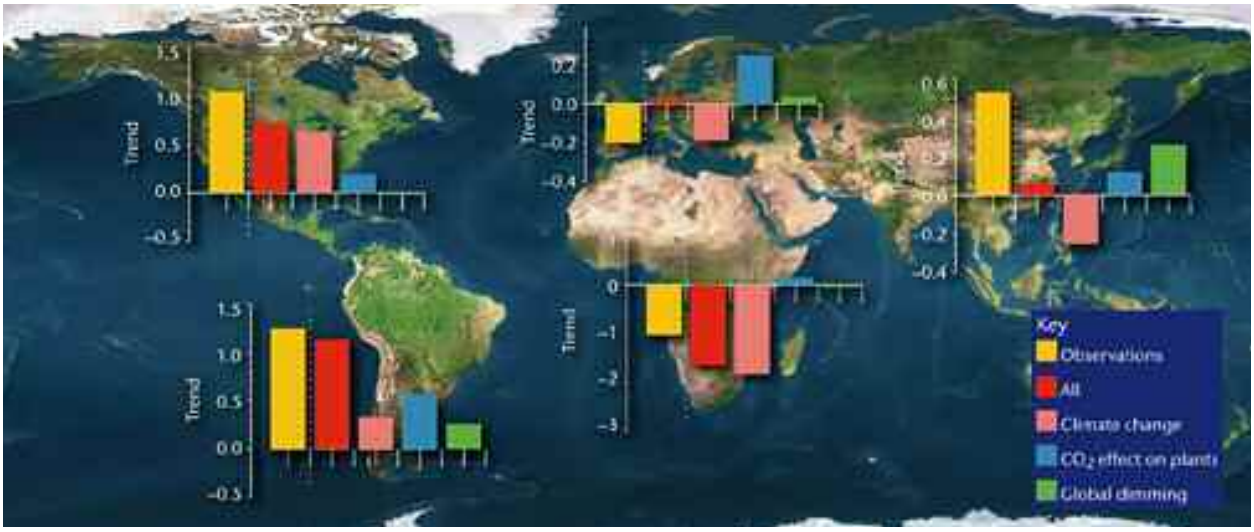
Changes in river flow have not been confined to the Arctic region. Observations suggest that continental river flow has been increasing during the 20th century, despite increasing use of water by man.

The main processes influencing the water cycle and river flow are: climate change and climate variability (and the associated changes in precipitation and evaporation), deforestation, global dimming, and the direct effects of atmospheric carbon dioxide increases on plant behaviour. In the latter process, increased atmospheric carbon dioxide leads to stomatal closure. This reduces transpiration from plants and, in turn, reduces the flux of moisture from the surface, leaving more water which can ultimately end up in rivers. Global dimming refers to a decrease in the amount of sunlight reaching the Earth's surface and is caused mainly by the presence of tiny airborne particles which either absorb the sun's radiation or reflect it back into Space. The Hadley Centre has generated model simulations in which these processes have been included individually in order to establish which are most likely to be causing the observed changes in river flow. Model simulations with all the processes included successfully capture year to year variations in the continental river flow. In some regions, such as South America, it is also able to adequately reproduce the changes in river flow observed after 1960. In others, such as Asia, it does less well.

We have used a sophisticated statistical technique which can account for errors in the magnitude of the model results, to reveal which processes make a detectable contribution to the observations. The effect of climate changes and the effect of CO_2 on plants both have detectable signals, whereas the effects of global dimming and land use change do not.

These results give the first tentative evidence that human induced increases in CO_2 are causing changes in river flow. These changes arise through the effect of CO_2 on plant transpiration. Changes in precipitation and evaporation, which may have both natural and man-made components, are also contributing to changes in river flow.

Post-1960 continental averaged trends (mm/yr/yr) in observed and simulated river flow. The individual contributions from the main processes affecting the water cycle are shown (note the different scales for each continent). The impact of land use is not included because it is small. (We acknowledge David Labat (Laboratoire de Mécanismes de Transferts en Géologie, UMR CNRS, Toulouse, France) for providing the observational runoff data)



Climate model simulations of future climate change

The Hadley Centre uses a range of climate models of differing complexity to make climate predictions. During the past year we have used our latest model, called HadGEM1 (Hadley Centre Global Environment Model version 1), for the first time.

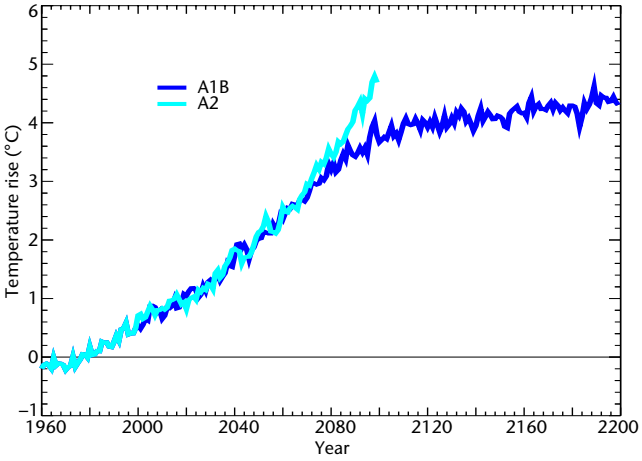
Like previous models, HadGEM1 represents the large-scale winds in the atmosphere and currents in the ocean, but this time on a finer scale. It also has major improvements in the way processes such as clouds, or the behaviour of the land surface are represented. The new representations are physically more realistic. In trials, HadGEM1 has outperformed our previous model in many areas, and it is still being improved.

The new model has been used to make a range of policy-relevant simulations, three of which are discussed here:

- SRES A2
  Total CO_2 emissions rise to around 29 GtC/yr
- SRES A1B
  Total CO_2 emissions rise to around 13.5 GtC/yr
- Stabilisation
  SRES A1B to 2100 and then fixed greenhouse gases

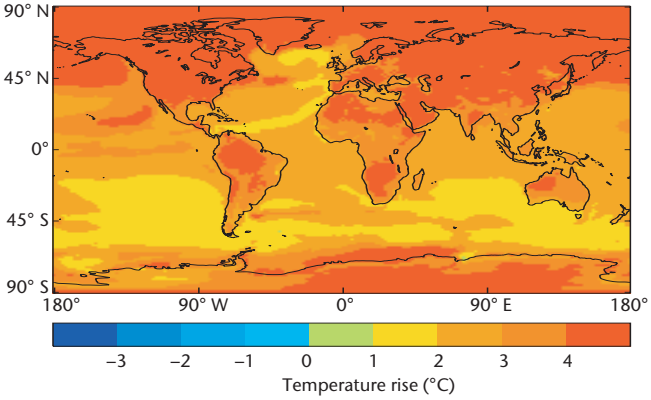
The global average warming projected for the 21st century is shown below. In the A1B simulation the 21st century warming is around 3.4 °C, slightly higher than estimates with the previous Hadley Centre model. This is probably due in part to the inclusion of black carbon aerosol, which enhances warming in contrast to other aerosols in the new model.

Global average temperature rises simulated for SRES emissions scenarios A1B (plus 22nd century forcing stabilisation) and A2



The 21st century spatial pattern of warming in the A1B simulation is also shown in the Figure below. As in previous simulations, the projected warming is greater over land than over the ocean and is amplified at high northern latitudes. These predictions are also within the range of climate model predictions noted by the IPCC in its third assessment report.

Predicted change in annual average temperature between the present day and late 21st century for the SRES emissions scenario A1B

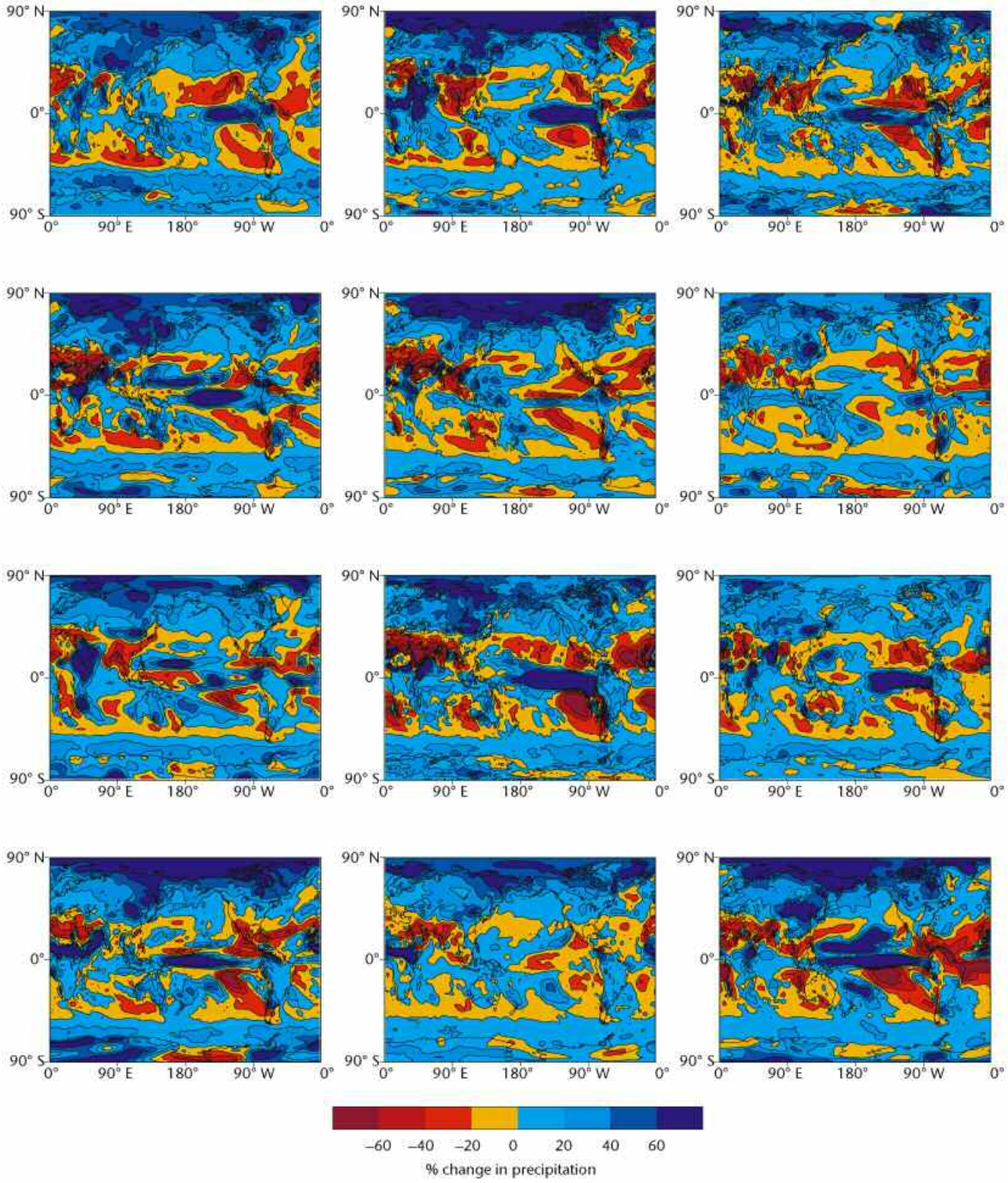


The water cycle in the new model is predicted to become more intense in the future. After 70 years of atmospheric CO_2 increases (at 1% compounded per year) the global average precipitation in HadGEM1 had increased by around 1% per °C of warming.

Single climate model simulations with a climate model such as HadGEM1 are very useful when trying to improve understanding of the response of the climate system to changes in forcing — an important step in improving predictions. They are also still used in sensitivity analyses. However, for century-scale predictions of policy-relevant quantities it is now also desirable to estimate the uncertainty in the predictions. In order to characterise, understand and ultimately reduce this uncertainty, results from many different models must be compared. The facing Figure shows the winter precipitation changes during the 21st century for the SRES A2 scenario from a subset of the models that will feature in the next IPCC assessment[2]. The global average changes range from approximately 1% to 6% in this subset.

[2] We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organising the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

Predicted changes in winter precipitation between present day and the late 21st century for the SRES A2 emissions scenario. The results are shown from a range of models taking part in the latest IPCC assessment

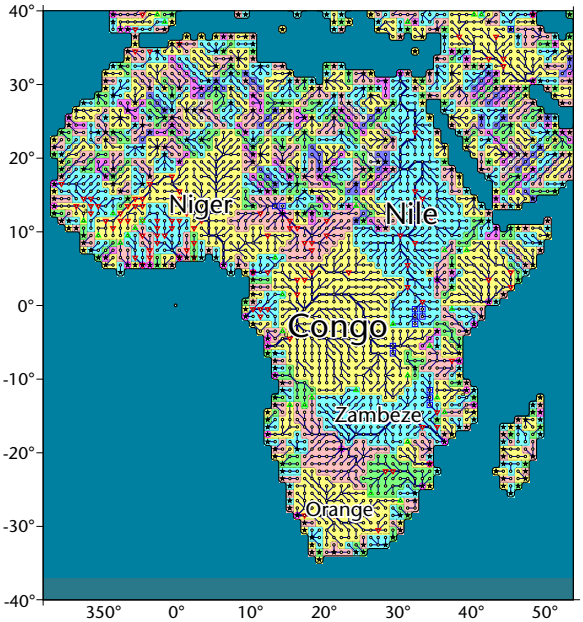


Predicted changes in 21st century river flow

River flow predictions

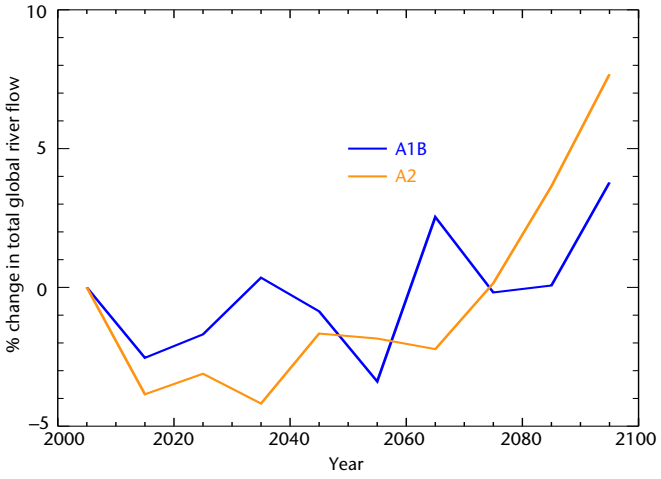
On pages 6 and 7 we presented the first predictions of 21st century temperature and precipitation from the new Hadley Centre climate model, HadGEM1. Here, we present predicted changes in river flow from this model. The manner in which rivers are simulated has been greatly improved compared to our earlier model. Tests of performance against observations show much better simulations of the seasonality and total amounts of river flow compared to simpler models. These simulations include the two most important processes identified on page 5, namely the direct effect of climate change and the effect of CO_2 on plants.

The rivers simulated in the African continent[3]



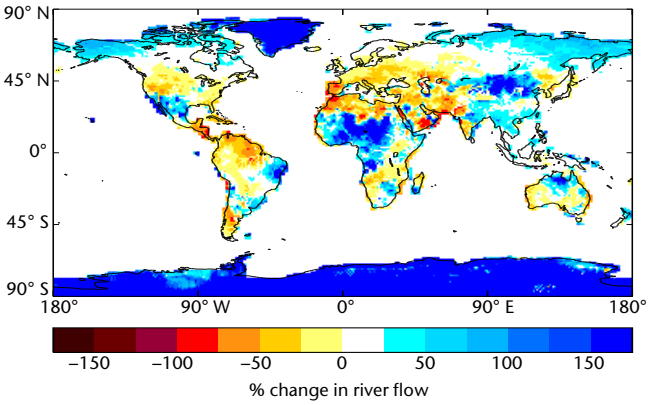
Predictions have been made for the SRES A1B and A2 scenarios. In both cases, global total river flow is predicted to decrease slightly until the middle of the 21st century, and then increase until 2100 (Figure below). The total 21st century increase in river flow is 4% and 8% for the A1B and A2 cases, respectively.

Predicted change in total global river flow during the 21st century for SRES emissions scenarios A1B and A2



There are large regional variations in the changes in river flow and the consequent impacts. There are large predicted reductions in river flow across much of Europe, North Africa, midwest America and northern South America, whilst large increases in river flow occur in West Africa, northern China and the boreal regions. Important changes in the seasonality of river flow could also occur, which are not shown here.

Predicted change in global river flow between present day and the late 21st century for SRES emissions scenario A1B



In future we aim to carry out an assessment of the uncertainty in these predictions of river flow changes. We are also making the results available as input into models of local flood risk.

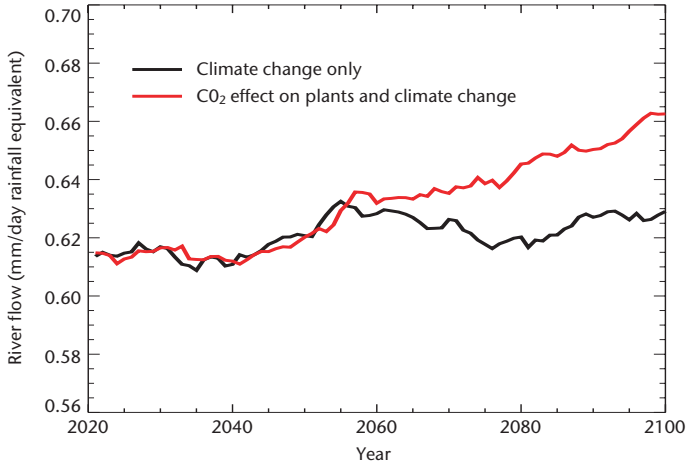
[3] T. Oki and Y. C Sud, Design of Total Runoff Integrating Pathways (TRIP) A global river channel network, Earth Interactions, 2, 1998

Effect of plant response on river flow during the 21st century

On this page we establish the relative importance of climate change and the direct effect of atmospheric CO_2 increases on plants in the future prediction of river flows. We made two future predictions for the 21st century. Both used a business-as-usual emissions scenario (IS92a – in which carbon emissions increase to around 20 GtC/yr by 2100) and a slightly less computationally expensive model than HadGEM1. Both simulations included radiatively driven climate change (i.e. changes in heating due to increases in greenhouse gases). One simulation included the direct effect of atmospheric CO_2 increases on plants while the other omitted it.

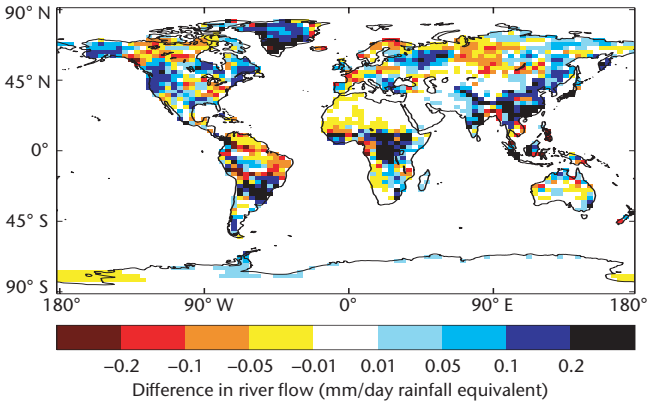
When the direct CO_2 effect on plants is omitted, the global average river flow is predicted to increase by 2% between the 2000–2020 and 2080–2100 periods. When the direct CO_2 effect is included, the predicted increase rises to 7%. Thus, the direct effect of CO_2 is predicted to be dominant on a global scale.

Predicted change in global average river flow during the 21st century for a business-as-usual scenario comparing the effects of climate change only with climate change and plant effects



The regional differences between the two simulations are more complex. When the effect of CO_2 on plants is included, much of the land surface shows more river flow but there are many regions where the river flow actually decreases. These latter regions tend to be those where the precipitation is reduced relative to the simulation without the plant transpiration effects. In these regions, decreased transpiration reduces the amount of water available in the atmosphere for precipitation.

Difference in the predicted changes in river flow between present day and the late 21st century when climate change and plant effects are included, compared to only including climate change



These results imply that an assessment of impacts should include the effects of plant behaviour. If this is not done, there is a risk that fluvial flood risk will be underestimated while droughts may be overestimated in some areas. It also highlights the need to consider the climate system behaviour as a whole, including both the physical and biological aspects.

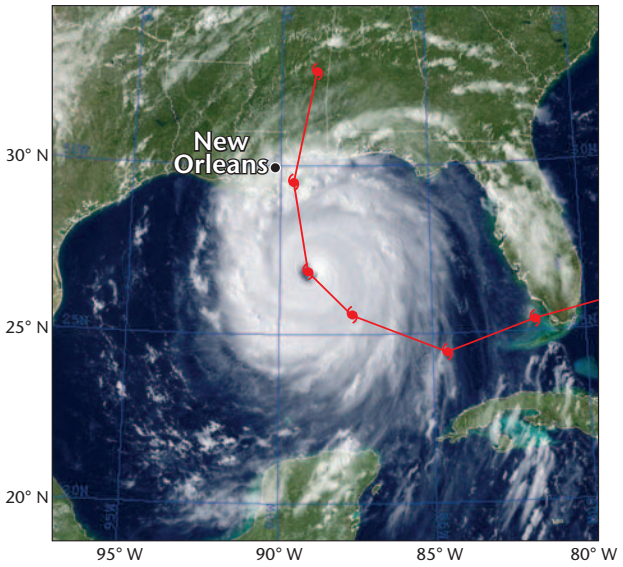
The effect of climate change on storms

Observed cyclones

Recent world events have demonstrated the vulnerability of coastal populations to intense tropical storms that form over the ocean then move towards the land; such as hurricanes in the Atlantic, tropical cyclones in the Indian ocean, and typhoons in the Pacific Ocean. During August 2005 the most financially costly Atlantic hurricane damage to date occurred when Hurricane Katrina struck the coast of the United States near New Orleans.

Katrina developed initially as a tropical depression but strengthened into a category 1 hurricane on 25 August. It then passed over parts of Florida and into the Gulf of Mexico, whose warm waters provided a potent source of energy which led to the storm's rapid intensification. Katrina finally achieved landfall on the morning of 29 August. The Figure below shows the observed track of the cyclone.

GOES-12 satellite image of Hurricane Katrina at 2045GMT on 28 August 2005, with the track of the storm superimposed[4]



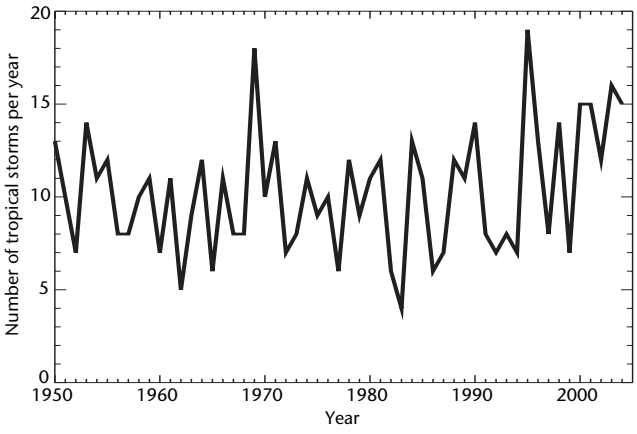
The strong winds associated with Katrina caused considerable damage. Additional damage resulted from the combination of extremely heavy rainfall and wind driven storm surges. The breaching of protective levees around New Orleans led to at least 75% of the city eventually becoming submerged.

The number of named Atlantic storms during 2005 has also been unusual. Up to 1 November there were 23 named stormed, breaking the previous record of 21 first set in 1933.

After a particularly damaging hurricane it is often asked whether it was caused by climate change. However, it is not yet possible to attribute a single weather event as being due to climate change. Instead, the hurricane must be viewed in the context of previous observed events.

The Figure below shows the frequency of Atlantic tropical storms, including hurricanes, from 1950. There is no apparent long-term trend, but there is a significant increase in the number of storms since 1995. In other parts of the world there is no trend. The increase in the Atlantic cannot yet be linked to human activities.

Observed number of North Atlantic tropical storms, including hurricanes[5]



The observational evidence from two recently-published studies[6] shows that the intensity of tropical storms, including hurricanes, has increased over the last 30 years. In particular, the number of the strongest category 4 and 5 hurricanes has doubled, while the number of weaker hurricanes has decreased. The overall increase in intensity may be more significant than an increase in frequency, if it causes more wind and flood damage.

4 satelite image from NOAA/National Climate Data Center.
5 The data are obtained from http://weather.unisys.com/hurricane/atlantic/index.html and we would like to acknowledge both UNISYS and the National Hurricane Center.
6 Emanuel K., Increasing destructiveness of tropical cyclones over the past 30 years, published online 31 July 2005 | doi: 10.1038/nature03906.
Webster P.J., G.J.Holland, J.A. Curry and H-R. Chang (2005), Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment, Science, 309, 1844-1846.

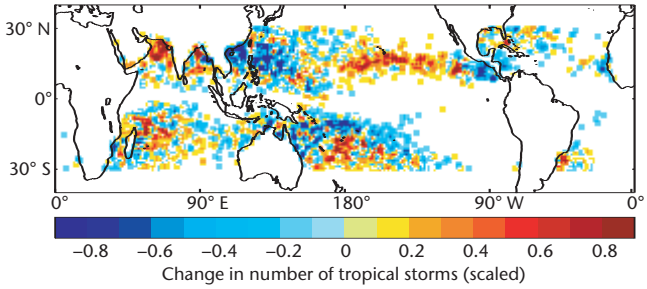
Future predictions of hurricane activity

For a hurricane to form, the temperature of the sea-surface must rise above 26.5 °C. However, a warm sea surface is not the only requirement; a complex set of atmospheric conditions is also necessary. For example, if there are stronger winds high up in the atmosphere but not near the surface then developing hurricanes are dispersed. The Hadley Centre is attempting to understand better the conditions necessary for tropical storm formation and to predict changes in the number and intensity during the 21st century.

Using a version of the Hadley Centre climate model, which can represent spatial details on a finer scale than the standard model, simulations were made of the present day (approximately 1980 to 2000) and a future period (approximately 2080 to 2100). In the future, the greenhouse gas emissions were assumed to have followed a business-as-usual scenario causing a global average warming of 3.6 °C.

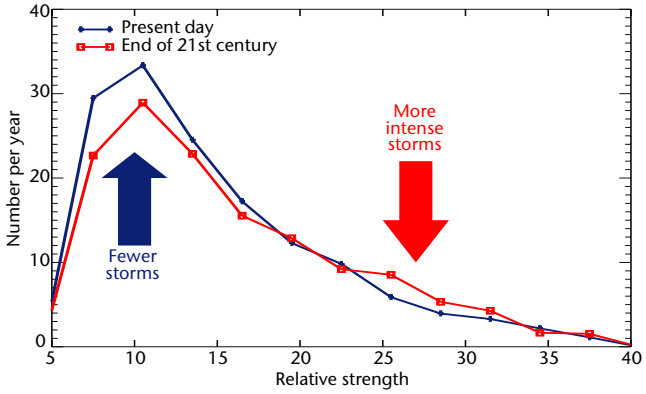
The number of storms predicted in the future experiment in the North Atlantic is less than that in the simulation of the recent past. There are also fewer storms in the north-west and south-west Pacific but more storms in the north-east Pacific and the Indian Ocean basin (Figure below).

Change in the number of storms between present day and the end of the 21st century



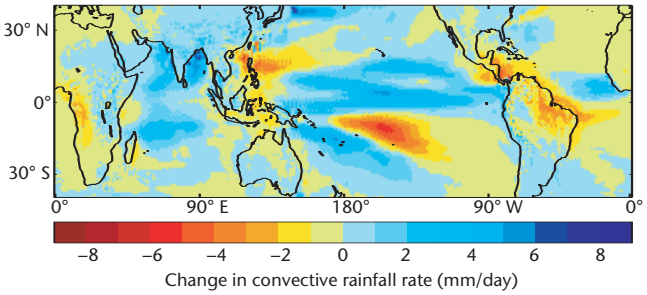
In contrast with the mixed signal in the change in frequency of storms, there is a clearer signal in their predicted change in intensity. The Figure below shows the frequency of storms with different intensities for the present and future periods. Globally, the number of weaker storms is predicted to decrease during the 21st century while the number of stronger storms is predicted to increase. The changes are small but statistically significant. This result is consistent with the recent changes observed in the Atlantic but does not prove that the observations are a result of climate change.

Change in the relative likelihood of storms of different strength between present day and the end of the 21st century



The damage caused by tropical storms is a result of the strong winds and heavy rainfall. Changes in rainfall associated with convective storms are shown in the Figure below. In some regions the increases in rainfall may be due to increases in the number of storms. However, since the number of storms does not increase everywhere, the changes in tropical storm intensity are clearly also important.

Change in the convective rainfall rate between present day and the end of the 21st century



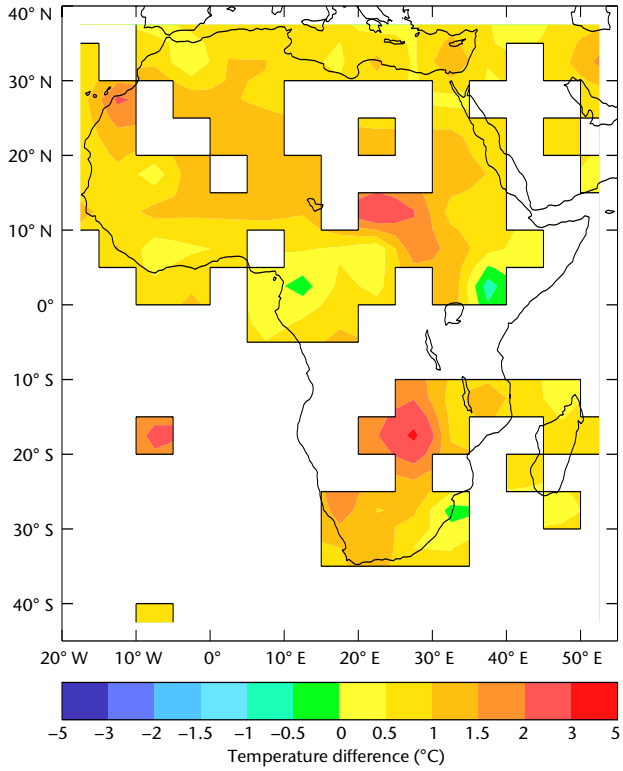
Thus, we have noted that there is evidence that tropical storm intensity has altered in recent years and models suggest that tropical storm numbers and intensity are very likely to alter in the future. The next step in our work will be to characterise the certainty of these model predictions.

The climate of Africa – a case study

Past changes

The 12-month period from August 2004 to July 2005 saw the warmest African temperatures on record. South of the equator, the temperature was 1.29 °C above the 1961–1990 average, a new record. North of the equator, the temperature was the joint warmest at 1.04 °C above average, equalling that for the same period in 1997–1998 (Figure below).

Observed temperature anomalies over Africa for a 12-month period, Aug 2004 to July 2005, relative to the 1961–1990 average



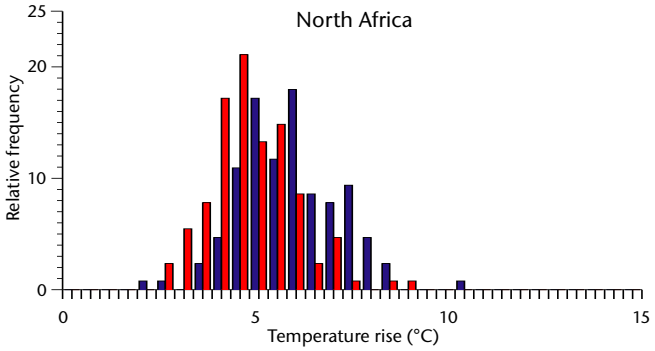
Large inter-decadal variations in rainfall in the African Sahel have been well documented. Since the 1980s, rainfall amounts in the Sahel have gradually increased. In 2004, the drought, combined with suitable meteorological conditions for locusts, led to the devastation of crops and resulted in food shortages in the western Sahel. In Summer 2005, rainfall replenished vegetation, but in some regions led to casualties from flooding as considerable amounts of water remained on the surface rather than being soaked up by the baked earth. Meanwhile, five-year-long drought conditions continued into 2005 in the Great Horn of Africa, offset partially with rains in May 2005.

Future predictions

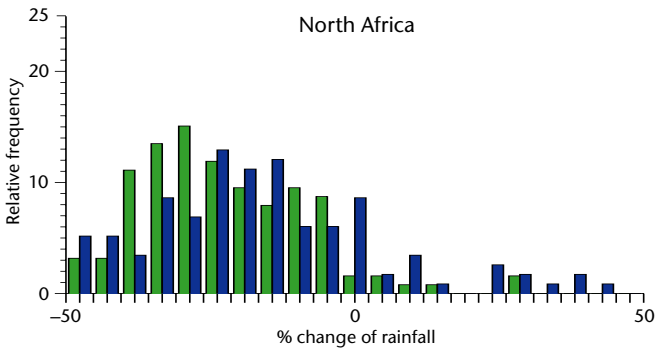
Climate model predictions of the future are most useful when they contain an estimate of uncertainty, enabling them to be used in quantitative risk assessments. The Hadley Centre is developing a technique in which a large number of slightly different but plausible versions of our climate model are used to predict the climate change over the same future period. The results are then used to construct a frequency distribution of predictions of, say, global average warming. Our ultimate goal is to not only quantify the uncertainty in predictions but also to reduce it.

This method has been used to predict the change in climate for a scenario in which atmospheric carbon dioxide concentrations were doubled. In the north of Africa the summer average temperature and the temperature of the warmest day of the summer are both most likely to rise by around 5 °C, although this could range between 2.5 and 8 °C. Summer rainfall is most likely to decrease but the wide spread of the result shows the high degree of uncertainty in this prediction. These increases in temperature and reductions in rainfall are likely to add to the problems already caused in this region by periodic drought.

Relative frequency of predicted changes in June, July and August daily maximum temperatures for the seasonal average (blue bars) and the hottest day of the season (99th percentile, red bars)



Relative frequency of predicted changes in June, July and August daily maximum rainfall for the seasonal average (green bars) and the wettest day of the season (99th percentile, blue bars)



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